Focus issue introduction: Advanced Solid-State Lasers (ASSL) 2015

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Abstract: The editors introduce the focus issue on "Advanced Solid-State Lasers (ASSL) 2015", which is based on the topics presented at a congress of the same name held in Berlin, Germany, from October 4 to October 9, 2015. This focus issue, jointly prepared by *Optics Express* and *Optical Materials Express*, includes 23 contributed papers (17 for *Optics Express* and 6 for *Optical Materials Express*) selected from the voluntary submissions from attendees who presented at the congress and have extended their work into complete research articles. We hope this focus issue offers a good snapshot of a variety of topical discussions held at the congress and will contribute to the further expansion of the associated research areas.

OCIS codes: (060.0060) Fiber optics and optical communications; (130.0130) Integrated optics; (140.0140) Lasers and laser optics; (160.0160) Materials; (190.0190) Nonlinear optics; (230.0230) Optical devices; (320.0320) Ultrafast optics.

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1. General information

Solid state lasers have underpinned major scientific and technological advances since Maiman's first laser demonstration in 1960 [1]. Over more than five decades, they have driven breakthroughs in science and technology and been at the core of fundamental discoveries which revolutioned our lives, as celebrated in 2015 by the UNESCO's International Year of Light and recognized by several Nobel prizes, the most recent ones being awarded for physics [2] and chemistry [3] in 2014. Solid state lasers in their many different forms, ranging from compact laser diodes to complex laser systems for high-energy physics and particle accelerators, have been key enablers for countless applications, encompassing spectroscopy, metrology, manufacturing, medicine and telecommunications, to name just a few, and continue to make a lasting impact on our daily lives.

The continuous progress in laser science and technology over the last decades has been underpinned by joint developments in materials, sources, and applications, for which the Advanced Solid State Lasers (ASSL) congress has established itself as the premier forum, offering researchers from all over the world the unique opportunity to present and discuss in one place their latest achievements, covering the full spectrum from basic material research, through system design and implementation, all the way to applied science and innovation. The current format of ASSL (2013-2015) builds on over 30 years of the OSA-managed, former TSSL (1985-1989), ASSL (1990-2002) and then joint ASSP-AIOM-FILAS (2003-2012) meetings [4]. Traditionally, the comprehensive scientific overview provided by the conference is accompanied by an active involvement of key industrial actors in the field, contributing also to the industrial exhibition associated with the ASSL conference.

It is therefore our pleasure to introduce here this joint focus issue of *Optics Express* and *Optical Materials Express* addressing topics of the ASSL 2015 congress held at the WISTA technology park in Berlin, on October 4-9, 2015. The ASSL congress was the third of its kind, following the ones in Paris, France (October 27 - November 1, 2013) and in Shanghai, China (November 16-21, 2014), highlighted in two previous focus issues [5,6].

The ASSL 2015 technical program featured 33 invited speakers, 7 postdeadline papers and more than 80 contributed talks in addition to poster sessions with 140 contributions [7]. Plenary sessions featured Denis Balitsky from Cristal Laser in France, Roberto Osellame from the Istituto di Fotonica e Nanotecnologie in Italy and Bedřich Rus from ELI Beamlines in the Czech Republic. The congress also featured a selection of short courses, complimentary for students, and a number of special events, which provided further inspiration and stimuli for interaction and networking among all attendees and colleagues. The social program featured a conference banquet with a talk by Holger Moench from Philips, celebrating also the International Year of Light. The rich industry program featured a panel discussion on current and future challenges in laser technology, a keynote presentation by Fredrich Dausinger on the development of disk lasers, a special workshop on how to communicate high tech to the market and to the wider public and a successful industrial exhibition, running in parallel with the conference and featuring more than 40 companies. All these events, together with the richness and variety of the scientific and industrial program and the overall conviviality of the congress allowed for lively discussions and stimulating exchanges among the conference participants, providing them with encouragement and inspiration to continue pushing forward new exciting developments and discoveries in the field of lasers, materials and their applications also for years to come.

2. Topical areas

2. 1 ASSL 2015 conference topics

The ASSL congress encompassed the full spectrum of materials, sources and applications.

The materials program brought together international experts and researchers to review and discuss the advances in optics, materials science, condensed matter physics and chemistry relevant for lasers and photonic components.

The sources program provided the most renowned forum to highlight advances in solid state lasers and other coherent sources, enhancing their performance in terms of: power, efficiency and brightness, wavelength coverage, spectral purity and stability, pulse durations.

The applications program concerned ways in which the advances in materials and sources highlighted by ASSL have an important impact on science and industry.

Technical advances in the different areas were further connected through two conference joint sessions, one for materials and sources, and the other one for sources and applications.

The 2015 ASSL conference topics were categorized as follows [7]:

- **Materials:** laser crystals and glasses; transparent ceramics; crystal and glass fibers; nonlinear crystals and processes; waveguides and laser patterning; photonic structures; semiconductors for lasers; LED and detectors; materials for lighting and laser display; advances in crystal growth techniques; modeling and characterization methods of laser and nonlinear properties.
- **Sources:** solid state lasers; fiber lasers; optical sources based on nonlinear frequency conversion; high power sources; infrared; visible and ultraviolet sources; laser beam combining and power scaling architectures; short-pulse lasers; frequency combs and frequency-stable lasers; microchip and compact lasers; tunable and new wavelength lasers; optically pumped semiconductor lasers.

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- **Applications:** lasers and laser systems with applications to medicine, manufacturing and emerging new fields.

2. 2 ASSL 2015 focus issue topics

This ASSL 2015 focus issue, jointly prepared by *Optics Express* and *Optical Materials Express*; includes 23 contributed papers (17 for *Optics Express* and 6 for *Optical Materials Express*) selected from the voluntary submissions from attendees who presented at the ASSL Congress 2015 and have extended their work into complete research articles.

The articles in this focus issue by no means can cover the whole range of research topics and contributions to the conference. However, they still allow sampling the breadth and depth of the presentations and discussions given at the congress and can give a flavour of the topics considered at the meeting, particularly in areas cathegorized as follows:

Optics Express

– Laser materials (2)

– Fiber lasers (3)

– Lasers and laser optics (1)

– Diode-pumped lasers (2)

– Q-switched lasers (2)

– Mode-locked lasers (1)

– Ultrafast lasers (2)

– Laser amplifiers (2)

– Nonlinear sources (2)

Optical Materials Express

– Laser materials (4)

– Magneto-optical materials (1)

– Mode-locked lasers (1)

The numbers given in parentheses in the above lists denote the number of contributed papers in the corresponding category. Each paper was attributed to a single category, which inevitably implies a simplification, as in most cases each contribution does cover multiple aspects. The next sections provide brief introductions to all the *Optics Express* and *Optical Materials Express* contributions. For each of them, after a short summary we indicate in parentheses the main category attributed to the paper and additional topical areas of furher relevance.

3. *Optics Express* contributions

3.1 Laser materials

Kurilchik, Gusakova, Demesh, Yasukevich, Kisel, Pavlyuk, and Kuleshov [8] investigate the main features of energy transfer and demonstrate diode-pumped microchip laser operation in Tm,Ho:KYW crystals. The parameters for Tm↔Ho energy transfer in Tm(5at.%), Ho(0.4at.%):KYW single crystals were determined from systematic measurements of the fluorescence dynamics and further confirmed by independent estimates obtained from the Förster-Dexter theory for dipole-dipole interactions. Diode-pumped continuous-wave laser operation was demonstrated in the TEM_{00}-mode, with a maximum output power of 77 mW at 2070 nm. (*Laser materials, diode-pumped lasers*, *infrared lasers*)

Mužík, Jelínek, Jambunathan, Miura, Smrž, Endo, Mocek, and Kubeček [9] report on a cryogenically-cooled $Yb:Y_3Ga_2Al_3O_{12}$ (Yb:YGAG) laser as a promising alternative to Yb:YAG, for short-pulse generation and amplification. They achieved SESAM mode-locking of a liquid-nitrogen-cooled Yb:YGAG ceramic laser operating at 1026 nm, yielding stable pulse trains at a 119-MHz repetition rate. The measured pulse duration (2.4 ps) was more than four times shorter than the one of a cryogenically-cooled Yb:YAG. Wavelength tunability and overall laser performance in continuous-wave operation at 80 K were also investigated. (*Laser materials, mode-locked lasers, cryogenically cooled lasers*)

3.2 Fiber lasers

Petkovšek, Novak and Agrež [10] demonstrate the concept of a fiber master oscillator power amplifier delivering pulses on demand with modulation bandwidths up to 40 MHz and output powers above 100 W in a quasi-CW regime. The laser system featured a dual-wavelength seed source, a double-stage Yb-doped fiber amplifier and a volume-Bragg-grating-for signal demultiplexing. The optimized system resulted in signal on-off contrast ratios of 25 dB. The joint experimental and numerical study indicated the possibility of transient minimizations in the sub-100μm range. (*Fiber lasers, laser amplifiers*)

Dvoretskiy, Lazarev, Voropaev, Rodnova, Sazonkin, Leonov, Pnev, Karasik and Krylov [11] report on the generation of high-energy ultra-short pulses in an all-fiber erbium-doped ring laser with a highly-nonlinear germanosilicate fiber. With a slightly positive net cavity group velocity dispersion, they obtained stable trains of 84 fs pulses with a central wavelength of 1560 nm and a spectral width of 48.1 nm, at a 12 MHz repetition rate. The output of the fibre oscillator featured an average power of 30 mW (29.7 kW peak power) and pulse energies of 2.5 nJ (*Fiber lasers, ultrashort lasers, nonlinear effects in fiber*)

Koška, Peterka, Aubrecht, Podrazký, Todorov, Becker, Baravets, Honzátko and Kašík [12] demonstrate pump absorption enhancement through the simultaneous coiling and twisting of thulium-doped fibers. The peak absorption of a 3m-long hexagonal thulium-doped fiber (14 dB) was found to increase by 8 dB through its coiling and twisting and the effect was further investigated with numerical modelling also for panda-type double-clad fibers. Under laser operation, the slope efficiency of a straight fiber (19.6%) was experimentally proven to increase to 23.9% with a simple fiber coiling and to 29.5% by a simultaneous coiling and twisting. (*Fiber lasers*)

3.3 Semiconductor lasers

Wen, Tuan, Liang, Tsou, Su, Huang and Chen [13] use a stack cavity design to demonstrate improved performance in a high-peak-power optically-pumped AlGaInAs laser with a silicon wafer as an output coupler. They compared a laser configuration involving a stack cavity, where the silicon wafer was directly bonded to the gain chip and its diamond heat spreader, with a conventional design, where the silicon wafer was separated from the other components. The experiments demonstrated enhanced laser stability and conversion efficiency for the Si-stack cavity, resulting in an average output power of 2.02 W with an overall optical-to-optical efficiency of 17.5% and a slope efficiency of 18.6%. The laser yielded a pulse peak power of 0.4 kW at a repetition rate of 100 kHz at 1.52 μm. (*Lasers and laser optics, semiconductor lasers, microchip lasers*)

3.4 Diode-pumped lasers

Ongstad, Guy and Chavez [14] report on a high power Nd:YAG spinning disk laser, generating 200 W of continuous-wave output power in a near diffraction-limited beam with 323 W of absorbed pump. They attained record conversion efficiencies of 63.6% in the CW regime and 63.3% in the pulsed regime (5 ms pulses at 10 Hz), indicative of good thermal

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management, achieved by rotating the 8 cm-diameter disk at 1200-1800 rpm with He-impingement cooling. The thermal dissipation per unit of output power (0.61 watt of heat per watt of laser output) was significantly below the typical range (0.8-1.1) of diode-pumped Nd:YAG lasers. (*Diode-pumped lasers*, *thermal management*, *disk lasers*)

Cho, Huang, Cheng, Huang, and Chen [15] investigate with theory and experiments the optimal temperature for cryogenic monolithic Nd:YAG lasers at 946 nm. They consider in detail the trade-offs associated with decreasing the temperature, which benefits quantum efficiencies by reducing the thermal population of the lower laser level, but at the same time decreases the pumping efficiency because of the narrowing of the medium absorption bandwidth. They find an optimal temperature to lie in the range of 120 K to 140 K, verify experimentally that a narrow-linewidth pump contributes to a more efficient output and further discuss additional issues affecting the choice of the optimum temperature. (*Diode-pumped lasers, cryogenic lasers*)

3.5 Pulsed lasers

Kausas and Taira [16] report on the generation of high-power and high-brightness Q-switched pulses in a $Nd:YVO_4$ microchip laser with a Cr^{4+}:YAG saturable absorber. The optimal operation resulted in the generation of giant pulses with an energy of 1 mJ and a peak power of 1.17 MW at a repetition rate of 100 kHz, achieved by a careful control of the emission cross-section and through the addition of a sapphire plate to homogenize the temperature and reduce thermal lensing in the gain medium. *(Q-switched lasers, diode-pumped lasers)*

Gao, Guo, Li, Lin, Yu, Zhang and Liang [17] investigate the potential use of $Nd:LuVO_4$ crystals in high average power and high repetition rate solid-state laser systems, demonstrating a picosecond mode-locked source providing an average power of 28 W at a repetition rate of 58 MHz. The shortest pulse duration, without dispersion compensation, was measured to be 4 ps. Cavity-dumping in the $Nd:LuVO_4$ oscillator enabled scaling the pulse energies up to 40.7 μJ at 300 kHz and 14.3 μJ at 1.5 MHz. (*Mode-locked lasers*)

3.6 Laser amplifiers and ultrafast systems

Mero, Noack, Bach, Petrov, and Vrakking [18] present a high-average-power, ultrashort-pulse optical parametric amplifier providing 90-μJ signal pulses at 1.55 μm and 45-μJ idler pulses at 3.1 μm at a repetition rate of 100 kHz. The signal pulses were recompressed to within a few percent of their ~50-fs Fourier limit, using anti-reflection coated fused silica with negligible losses. The overall energy conversion efficiency from the 1030-nm pump to the recompressed signal reached 19%, significantly reducing the cost per watt of pump power compared to similar systems. Perspective applications of the two-stage source include its use as the front-end of a three-stage system for ultrafast imaging of molecular structures and chemical reactivity. (*Ultrafast lasers, laser amplifiers, nonlinear sources*)

Vasilyev, Moskalev, M. Mirov, S. Mirov and Gapontsev [19] demonstrate efficient amplification of few-optical-cycle mid-infrared pulses in continuously-pumped polycrystalline Cr^{2+}:ZnS and Cr^{2+}:ZnSe gain media, spanning the infrared spectrum between 2.0 and 2.6 μm. The 1.7 W output of a Kerr-lens mode-locked master oscillator with a 2.4 μm central wavelength and a 79 MHz repetition rate was amplified to 7.1 W and 2.7 W in Cr^{2+}:ZnS and Cr^{2+}:ZnSe, respectively. The high peak power of the input pulses (0.5 MW) and the high nonlinearity of the gain media resulted in spectral broadening and significant shortening of the output pulses. Transform-limited pulses produced by the master oscillator were compressed to about 27–30 fs. The spectrum of the pulses was broadened from 136 nm to 450 nm (at −3 dB level), with a span exceeding 600 nm at −10 dB. (*Ultrafast lasers, laser amplifiers*, *mode-locked lasers, nonlinear effects*)

Von Grafenstein, Bock, Ueberschaer, Griebner and Elsaesser [20] report on a 2 μm multi-stage amplifier delivering picosecond pulses with energies as high as 34 mJ at 1 kHz repetition rates. The system was based on Ho:YLF and featured a continuous-wave pumped,

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high-gain regenerative amplifier that enabled the generation of stable pulses with energies above 10 mJ in a double-pulsing periodic regime and acted as seed source for a single-pass booster amplifier running at room temperature. Stable pulse trains with energy of up to 34 mJ were achieved by single-pass amplification in a Ho:YLF rod, corresponding to an average output of 34 W. The recorded complete bifurcation diagram of the regenerative amplifier agreed well with numerical simulations. At the highest pulse energy after the booster amplifier, pulse-to-pulse fluctuations were as low as 0.9% rms. Pulse compression performed up to the 10-mJ level resulted in a final ouput pulsewidth of 37 ps. (*Laser amplifiers, nonlinear effects*)

Chvykov, Nagymihaly, Cao, Kalashnikov and Osvay [21] put forward the design of an amplifier for high peak and average power Ti:sapphire systems. The design combines thin disk laser technology and a scheme for extraction during pumping in order to overcome limitations associated with thermal cooling of the gain medium and transverse amplified spontaneous emission. With it, the authors envisage scaling up Ti:sapphire systems to attain output peak powers in the PW range, with kW-level average powers. (*Laser amplifiers*, *disk lasers, thermal management*)

3.7 Nonlinear effects

Boyko Marchev, Petrov, Pasiskevicius, Kolker, Zukauskas and Kostyukova [22] investigate intracavity-pumped cascaded optical parametric oscillators (OPO) with idler outputs in the 5.8-18 µm range based on $AgGaSe_2$. The $AgGaSe_2$ nonlinear crystals were intracavity-pumped by a doubly-resonant optical parametric oscillator based on Rb-doped periodically poled KTP, pumped at 1.064-µm and generating signal pulses at ~1.85-µm, at a repetition rate of 100 Hz. The maximum mid-IR pulse energy reached 171 µJ at 11.46 µm. By resorting to different crystal cuts, for type-I and type-II phase-matching, the singly-resonant $AgGeSe_2$ OPO covered the full spectral range between 5.8 and 18 µm. (*Nonlinear sources*, *mid-infrared sources*)

Ishizuki and Taira [23] demonstrate high-gain mid-infrared optical parametric generation in a single-pass configuration by using large-aperture periodically poled Mg-doped $LiNbO_3$ (PPMgLN) crystals pumped by a Q-switched sub-nanosecond microchip laser. Effective mid-infrared wavelength conversion with 1 mJ output energies and broadband optical parametric generation from 1.7 to 2.6 µm were realized by using strictly periodic and chirped PPMgLN gratings, respectively. (*Nonlinear sources, periodically poled materials, mid-infrared sources*)

3.8 Applications

Pavel, Dascalu, Salamu, Dinca, Boicea and Birtas [24] explore the potential of laser technology for gasoline engines. They report on the design and implementation of a laser ignition system for automobile engines based on high-peak power Q-switched Nd:YAG/Cr^{4+}:YAG lasers. The system delivered 0.8 ns pulses with an energy of 4 mJ and a peak power of 5 MW. It was used to operate a Renault car engine and assess its performance for engine speeds ranging from 1500 to 2000 rpm and high (up to 920 mbar) loads. Improved engine stability and decreased emissions of CO and HC gases were found as a result of igniting the engine with laser sparks instead of classical electrical spark plugs. (*Q-switched lasers, microchip lasers*)

4. ***Optical Materials Express*** contributions

4.1 Laser materials

Grant-Jacob, Beecher, Parsonage, Hua, Mackenzie, Shepherd and Eason [25] present details of pulsed laser deposition of Yb:YAG films onto a <100> oriented YAG substrate, in which they also demonstrate laser action. The high quality of the homo-epitaxial active layers

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deposited on YAG was assessed by X-ray diffraction and spectroscopic measurements. Lasing was demonstrated with a 15 μm-thick Yb:YAG planar waveguide generating 11.5 W of output power with a slope efficiency of 48%. The work indicates the viability of high-quality single-crystal Yb:YAG growth via pulsed laser deposition, with characteristics comparable to those obtained via conventional crystal growth techniques. (*Laser materials, thin films, waveguide lasers*)

Farukhshin, Nizamutdinov, Korableva and Semashko [26] demonstrate short-pulse laser oscillation in the ultraviolet achieved in $Ce:LiY_{0.3}Lu_{0.7}F_4$, a promising crystal for its peculiar photodynamic properties, which enable its simultaneous operation as an active medium and a Q-switching device. Lasing at 311 nm with a slope efficiency of 6% was obtained for pumping at 289 nm with 6 ns pulses at 10 Hz. The $LiY_{0.3}Lu_{0.7}F_4:Ce^{3+}$ laser produced sub-ns (400 ps) output pulses, as a result of a intracavity loss-modulation induced by color-centre bleaching occurring in the very same gain material. (*Laser materials, ultraviolet, pulsed lasers, Q-switching*).

Ma, Su, Xu, Wang, Jiang, Zheng, Fan, Li, Liu and Xu [27] investigate the effect of erbium concentration on the spectroscopic properties and the laser performance of $Er:CaF_2$ crystals at 2.79 μm. Erbium concentrations of 4 and 8 at.% provided the largest cross-sections for absorption at 967 nm (0.22×10^{-20} and 0.23×10^{-20} cm^2, respectively) and emission at 2727 nm ($\sim 0.67 \times 10^{-20}$ cm^2). The lifetime of ${}^4I_{13/2}$ was found to decrease faster than that of ${}^4I_{11/2}$ for increasing concentrations. Continuous-wave laser operation around 2.79 μm was achieved for samples with 4, 8 and 11 at.% doping. The concentration of 4 at.% yielded the best laser performance, with a maximum output power of 0.282 W and a slope efficiency of 13.9%. (*Laser materials, mid-infrared lasers*)

Serres, Jambunathan, Loiko, Mateos, Yu, Zhang, Liu, Lucianetti, Mocek, Yumashev, Griebner, Petrov, Aguiló and Díaz [28] present a comprehensive study on continuous-wave laser operation and thermal lensing in Yb-doped gallium garnets under diode-pumping at ~932 and 969 nm. Their experiments showed that despite exhibiting lower thermal conductivities than Yb:YAG, ordered Yb:YGG and Yb:LuGG crystals are most promising for compact and highly efficient microchip lasers. By pumping Yb:LuGG crystals at 932 nm (969 nm) the authors obtained emission in the 1039–1078 nm range, with a lasing output power of 8.97 W (9.31 W) and 75% (65%) slope efficiency. The sensitivity factor for thermal lensing in the crystal was estimated to be 2.1 m^{-1} /W and the thermal conductivity 5.8 ± 0.5 W/mK. Poorer thermo-optic properties and higher internal losses appeared instead to limit the power scaling capabilities of microchip lasers in Yb:CNGG and Yb:CLNGG. (*Laser materials, diode-pumped lasers*)

4.5 Magneto-optical materials

Furuse, Yasuhara, Hiraga and Zhou [29] report on the observation of enhanced magneto-optical properties in Ti-doped terbium aluminum garnet (Ti:TAG) ceramics. The temperature dependence of the Verdet constant of the material was investigated at 632.8 and 1064 nm. The Verdet constants measured at the two wavelengths amounted to 184 and 53 rad/Tm, respectively at 296 K. The Verdet constant of the Ti:TAG ceramics at 1064 nm, where the sample transmittance was around 75%, was ~1.5 times higher than that of terbium gallium garnet (TGG). The results indicate Ti:TAG ceramics as possible candidates for the implementation of high-power Faraday isolators. (*Magneto-optical materials*, *optical isolators*)

4.6 Mid-infrared mode-locked lasers

Wang, Xie, Xu, Di, Qin, Suomalainen, Guina, Härkönen, Agnesi, Griebner, Mateos, Loiko and Petrov [30] demonstrate the successful passive mode-locking of a $Tm^{3+}:CaGdAlO_4$ (Tm:CALGO) laser operating near 2 μm, yielding pulse durations of ~650 fs at a repetition rate of ~100 MHz. In CW operation the Tm:CALGO laser featured spectral tunability over

254 nm. With a GaSb-based SESAM, clean mode-locking without any Q-switching instability was achieved. Careful cavity optimization resulted in the generation of $sech^2$-shaped pulses with durations as short as 646 fs. Their spectral bandwidth around the 2021 nm central wavelength was 9.2 nm, yielding a time-bandwidth product of ~0.44. The results indicate the potential for achieving even shorter pulse durations, by overcoming the limitations imposed by the recovery time of the SESAM. (*Mode-locked lasers, mid-infrared ultrafast sources*)

5. Conclusion

In conclusion, we witnessed the success of the ASSL 2015 congress as the only international, integrated event regarding solid-state lasers, running single-track technical sessions for materials, sources, and applications. We hope this focus issue provides a flavour for the variety of topical discussions held at the conference in 2015, contributing to further advances in the associated research areas.

We believe that joining in this exciting meeting in the future shall continue to offer great opportunities for seeing the utmost recent advances in solid-state laser science, and invite you to join the upcoming ASSL Congress 2016 to be held in Boston, Massachusetts, from October 30 to November 4, 2016.

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